# Towards the quantitative analysis of the electron holographic phase images of electrically biased metal tips

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# Towards the quantitative analysis of the electron holographic phase images of electrically biased metal tips

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Measurements of the electrostatic potentials of metal tips, such as those prepared for field emission, atom probe microscopy or atomic force microscopy, may be carried out quantitatively using off-axis electron holography in the transmission electron microscope (TEM). Here, we present the results of electron holographic observations of a tungsten tip and develop a model that can be used to interpret experimental phase images to extract a quantitative measure of the electric field in close proximity to the tip.

Off-axis electron holograms of an electrically biased tungsten tip were acquired at an accelerating voltage of 300 kV using an FEI Titan field emission gun TEM equipped with a Lorentz lens, an electron biprism, a Gatan imaging filter and a 2048 pixel charge-coupled device camera. A reference hologram was acquired immediately after each specimen hologram and used to remove distortions associated with the imaging and recording system of the microscope. Figure 1(a) shows a representative electron hologram of the tip. Additional holograms were acquired after varying the applied bias between the tip and a gold counter-electrode located ~10 $\mu$m away. Reconstructed phase images (2x amplified) are shown in Figs 1(b-d) for bias voltages of 0, 10 and 20 V, respectively. The phase gradient, and hence the variation in electric potential and field, can be seen to increase with applied bias.

In order to recover quantitative information from the phase images, a simple model for the electrostatic field was developed by considering the electrostatic potential generated by a line of charges with a density that increases linearly with distance from a conducting plane [1,2]. When the electrostatic potential of a uniform field is added throughout space, the resulting potential contains an ellipsoidal null equipotential surface with rotational symmetry around the charged line. Such an equipotential surface mimics very well at its end the shape of a metallic tip thinned by standard chemical methods, such as that shown in Fig. 1(a). This approach also has the advantage that the electron optical phase shift can be expressed analytically [3].

The procedure is as follows: i) The shape of the ellipsoid is constrained by setting its major semi-axis equal to the tip length; ii) The minor semi-axis is then fitted to the tip outline provided by its image at Gaussian focus; iii) Having fixed the tip shape (i.e., the geometrical parameters), a set of image simulations with varying charge density profiles is calculated and compared with the experimental phase images to determine the best-fitting slope of the linear charge density.

Figure 2 shows the result of the comparison between simulations and experimental measurements for a 10 V applied bias. In the frame on the left, the geometrical parameters are determined, yielding an ellipsoid with an aspect ratio of ~1000. On the right, experimental and simulated phase images are shown in the form of 2x amplified phase contours (i.e., each bright or dark fringe spacing represents a $\pi$ phase shift). The agreement in terms of phase topography appears to be very good, with the exception of minor discrepancies in the sharpness of the phase fringes along the outer tip axis, most likely due to differences in the radius of curvature of the tip apex. The experimental tip was in fact slightly damaged or degraded at its end, preventing exact fitting of its outer shape with a single ellipsoid.

These preliminary results also suggest a possible way of improving the measurements. As shown by Jaeger et al. [4], the superposition of several line charges, resulting in a non-linearly increasing charge density, can be used to model non-ellipsoidal null-equipotentials to provide better fits to real tip shapes. A refinement procedure based on this approach, possibly coupled with the acquisition of holograms with the tip rotated about its axis to assess the degree of rotational symmetry present, could lead to a better fit of the experimental results and hence to a fully quantitative evaluation of the electric field around the tip [5].

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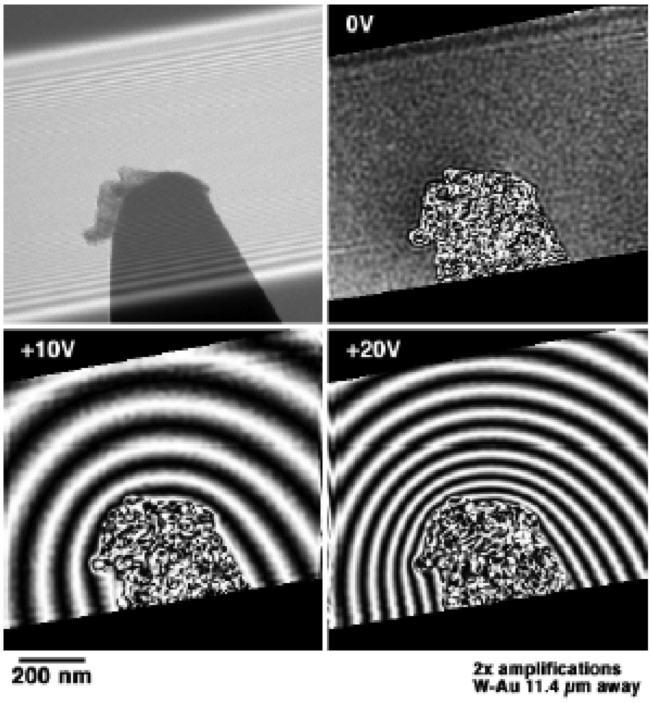


***Figure 1.*** *(a) Off-axis electron hologram of an unbiased tungsten tip acquired at 300 kV. (b-d) Reconstructed 2x amplified phase images for applied bias values of 0, 10 and 20 V, respectively, between the tip and a gold counter-electrode located ~10 $\mu$m away.*

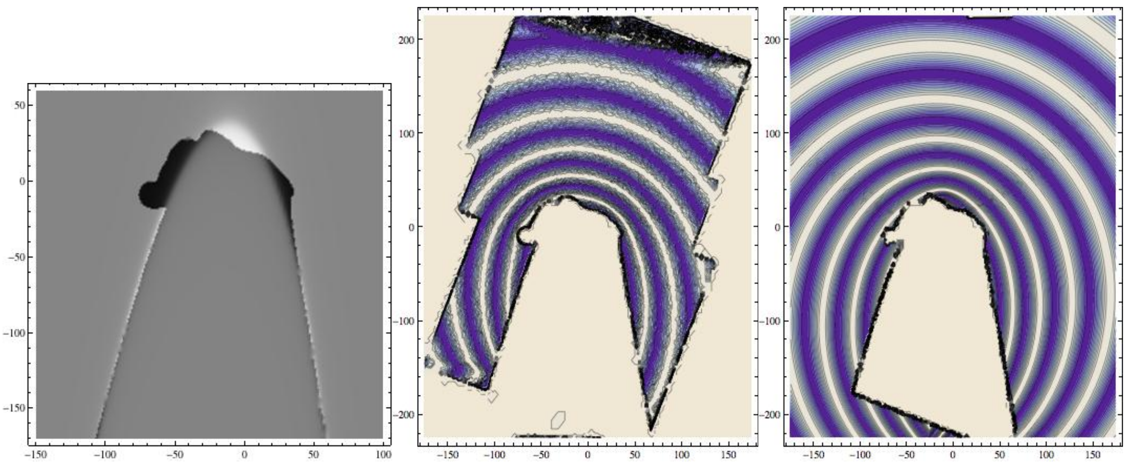

***Figure 2.*** *Left: Best-fitting tip shape parameters describing the major and minor semi-axes of the ellipsoidal null equipotential. Middle: Experimental 2x amplified phase image reconstructed from a hologram acquired with a 10 V applied bias. Right: Corresponding best-fitting simulated phase image, with the experimental tip outline superimposed.*